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Toward a Survivability/Lethality Analysis Directorate (SLAD) Methodology for Conducting System of Systems Analysis (SoSA)

by Jeffrey A. Smith and Michael W. Starks

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14. ABSTRACT
The Survivability/Lethality Analysis Directorate (SLAD) of the U.S. Army Research Laboratory (ARL) provides survivability, lethality, and vulnerability analyses and expert technical consultation on survivability matters. Traditionally, these analyses focused on single items analyzed in isolation; while still important, this focus is insufficient to address the current needs of SLAD's most important customers including U.S. Army Test and Evaluation command (ATEC) and Program Executive Offices (PEOs) Program Managers (PMs). In order to enable the required force operating capabilities, Army leadership is defining and developing complex system of systems (SoS) suites of technologies called "capability packages." This report documents *how* we are analyzing technologies and capability packages in a mission based SoS context.

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As the U.S. Army Research Laboratory (ARL)—Physical Science Laboratory (PSL) team developed this methodology over the past few years, the authors have had many wide ranging and illuminating discussions on what it means to conduct system of systems analysis (SoSA) in a military operational environment. Mr. Richard Flores and Ms. Jill Thompson of ARL have been prominent in many of these discussions, as have Dr. Ray Bernstein; Mr. Jim Davidson, LTC, U.S. Army (RET); Dr Roger Hartley; and Dr. Alex Pogel of New Mexico State University/PSL. The last three also provided the source material we adapted for figures 1, 2, and 4 as well as table 2. We received valuable executive perspective on Army-level requirements for a SoSA tool such as System of Systems Survivability Simulation (S4) from Dr. Jim Streilein (formerly ATEC), Brian Simmons (ATEC), Dr. William Crain (AMSAA), and Mr. John Miller (ARL).

Special thanks to the members of the Survivability/Lethality and Analysis Directorate (SLAD) SoSA Integrated Process Team (IPT): Mr. Peter Bother and Dr. Patrick Honan, EW subject matter experts; Mr. Anthony Castañares and Dr. John Medrano, computer network operations (CNO) subject matter experts; and Ms. Rebecca Young and Mr. Ron Bowers, ballistic subject matter experts. In addition, we thank Mr. Brad Morgan and Mr. Joel Eichelberger who provided invaluable software subject matter expertise.

1. Introduction

In this introduction, we present a brief background discussion to make clear the technical context of our work. Next is an explanation of three system of systems analysis (SoSA) application regimes—use cases—that emerged from our discussions across the Army analysis community. The main point of the report comes next: we describe how we use our SoSA methodology to analyze the three types of use cases. We conclude the body of the report with a visual metaphor that links the various elements of our methodology together. In an appendix, we provide a discussion of some specialized terminology regarding system of systems (SoS), system of systems engineering (SoSE), SoSA, and others.

The U.S Army Research Laboratory's (ARL's) Survivability/Lethality and Analysis Directorate's (SLAD's) mission is to provide survivability, lethality, and vulnerability analyses (SLVA) and expert consultation to its customers. Important customers include the Army's independent evaluator Army Test and Evaluation Command (ATEC), program managers (PMs), and Army decision makers. Traditionally, this activity focused on single-thread analyses; such analyses characterize the interaction between a single item of equipment and one or more threats as if that interaction took place in isolation from all else. Although SLVA of individual items remains important, it is no longer sufficient to address the technical and business concerns of many SLAD customers. The newer concerns are inherently at the SoSA level. Army and defense leadership is intent on fielding a network-enabled force and acquiring complex packages of military capabilities that will support the full range of Force Operating Capabilities[*]. Comprehensive analysis of these packages requires us to portray the results from subtle engineering interactions among different systems in the capability packages. We must consider the whole SoS (*2*).

SLAD is simultaneously using and further developing the System of Systems Survivability Simulation (S4) (*3*) to approach these broader survivability issues. Because S4 provides the ability to analyze capability packages in a mission context, SLAD analysts are no longer limited to tools that work only for single-thread analysis. We use S4 to illuminate higher-level complexities and interactions in the context of explicit operational missions. By assessing survivability issues in the context of relevant operational missions, analysts can now provide metrics that address broader and more subtle analytical questions that have been beyond the reach of single-thread analysis. The results are also more relevant to the warfighter because we develop them in an operational rather than a merely technical context.

[*] TRADOC Pamphlet 525-66 (*1*) entitled "Force Operating Capabilities" discusses the required capabilities in tactical detail.

Two years ago, SLAD began integrating engineering-level threat effects into S4. We created the necessary scaffolding to demonstrate SoSA of ballistics, computer network operations (CNO), and electronic warfare (EW) threats, both individually and in combination. This success proved that we could produce survivability analysis that provided value added with respect to results from single-thread analysis. Naturally, SLAD's mission dictated that we design that first framework principally to illuminate survivability issues, considered in a SoS context. However, as we have presented our model and early results to interested parties and executive leadership in the Army community, we found that there was strong demand for use of our tools to solve problems beyond technical survivability analysis. The next section addresses how we conceptualized this expansion.

2. Use Cases for SoSA Application

During the collaborations mentioned in the previous paragraph, we found that clearly identifying the top-level purpose of a given SoSA greatly reduced miscommunication. We eventually distinguished three types of application for SLAD's SoSA. Though these are broad classes rather than specific problems, we chose, in a slight abuse of terminology, to call each of them a *use case*. Traditional survivability disciplines constitute our use case 1. SLAD analysts involved in use case 1 threat work have developed significant familiarity with SoSA tools and methods, and are helping inculcate the broader perspective into the wider workforce.

SLAD has also responded to customer demand for SoSA that is beyond use case 1. Use case 2 analyses support ARL goals in science and technology. Use case 3 supports engineering evaluations. The three use cases demarcate SLAD's intended SoSA scope. We can characterize the use cases by the type of SoS problem addressed and the associated analytic approach.

Use case 1 reflects SLAD's core mission of conducting SLVA with respect to ballistics, EW, and CNO threat effects in a SoS context. This use case requires an engineering-level representation of at least some of the technologies analyzed, high fidelity threat effects, and a corresponding vignette that establishes a representative mission context. Operational and technical analysis is required but with emphasis on the survivability, lethality, and vulnerability (SLV) technical area.

Use case 2 focuses on science and technology rather than SLAD's traditional mission of systems analysis. The intent here is to exploit synergies between ARL's technical core competencies and the analytical infrastructure available with S4 and the SoSA methodology. This use case provides a testbed for research and development, and an analysis capability to evaluate alternative technologies early in the product life cycle.

Use case 3 reflects SLAD's response to changes in the way the Army acquires technical capabilities for its forces. The Army Force Generation (ARFORGEN) Process (*4*) aims to move the Army from a garrison-based, tiered deployment scheme based on divisions to one based on brigades. The overall goal is to deliver refreshed and properly equipped troops to combat theaters on a cyclical basis, and to structure the entire institutional Army to support those deployment schedules. The acquisition community's contribution is rapid insertions of technology via *capability packages*. Briefly, a capability package is a set of prioritized solutions that are adaptive and tailored to mitigate high-risk gaps in a particular force operating capability. As a brigade enters a regeneration cycle, the Army will improve its existing capability by insertion of the latest capability package.

Both the acquisition community and the evaluation community are responding to this major change by seeking out new methods to fulfill their missions. The materiel developers need a method to analyze whether, and to what extent, the packages of technologies they are developing can improve warfighter capability in relation to the money spent. Such analyses determine, for example, whether improvements in achieving tactical missions warrant the expense of changing from a minimum threshold requirement to a desired but more expensive objective requirement.

The evaluation community must also determine the impacts of proposed capability packages, the interactions between and among them, and the potential challenges they bring. Many believe that the ideal evaluation method is SoS user tests or other such field experiments. However, such activities are complex and quite expensive to conduct, as well as being inherently limited in sample size. For such tests, the analyst often wonders whether, and to what extent, the measured result approximates a measure of central tendency. A SoSA capability can be invaluable here in screening technical issues for relative importance and sifting priorities so that the most important are tested.

For the use case 3 applications, S4 provides a convenient platform with which to develop engineering level SoSA assessments. The emphasis is on how the performance of a system under test (SUT) affects overall mission success. The evaluation criteria drive the representation of the SUT and the measures of performance (MOP); therefore, in many cases we need not simulate those properties of the represented systems that are not relevant to the specific evaluation issues at hand. For example, the weight of a system might be critical for some analyses where mobility is an issue. If mobility is not under study, we may not find it necessary to represent it precisely in the model.

To summarize these application regimes, use case 1 is SLAD's approach to providing a foundational SoS context for our more traditional SLV analyses. Use cases 2 and 3 represent different classes of efforts to extend SoSA to early technology development on the one hand, and to systems evaluated for production and deployment on the other. Together, these three use cases provide the Army with a comprehensive approach to SoSA for new technologies. We summarize the use cases in table 1.

Table 1. Examples of each use case in terms of the problem we expect to address, the questions we expect to ask, how we expect to answer that question, and our potential customers for that response.

		Use Case					
		1: Threat Effects			**2: Tech Base**	**3: Engineering Evaluation**	
		Ballistics	**EW**	**CNO**		**Systems Engineering**	**Capabilities Package**
Example	**Problem**	Mission based SLVA of networked-enabled small units subject to one or more threats.			Mission based early evaluation of technology characteristics.	"On demand" analysis of technology "what if" questions to optimize system-engineering design.	Evaluate capability packages.
	Analysis Question	Will a known vulnerability to a system have an impact on a warfighter operating in a mission context?			What are the impacts to mission outcomes and message latency for two different intrusion detection techniques when applied to a mobile ad hoc network supporting forces in a mission context?	Which capability package systems enhance the accuracy and completeness of the Blue leader's situational awareness?	
	Analysis Approach	Engineering level representation of the SoS under test (SUT), vignette establishes context for mission evaluation.			Emulate a technology in mission context for evaluation.	Established set of vignettes for evaluation; SUT representation and MOP driven by evaluation criteria; Comparison of fielded, current and future capability packages.	
	Customer	SLAD, AEC, PMs			ARL; RDECs	ATEC; PEO-I	

As SLAD conducts analyses of these three use case types over the next years we will evolve a strong foundation for further decisions on the pace of change—the long-term plan—in each of the three application areas. At present, our SoSA/S4 capability has reached a state of maturity wherein external customers have asked us to use it to illuminate SoSA issues that are relevant to them. We describe our present practice in responding to these customers in the following section.

3. Methodology

The principal aim of this paper is to clearly state SLAD's current practice for conducting SoSA. Although we hope that our treatment is sufficiently general to apply to any of the three use cases, we realize that since engineering-level SoSA is a new discipline, it will surely continue to evolve. Our present practice consists of five phases:

1. Define the Problem.
2. Develop the Model.
3. Build the Simulation.
4. Evaluate the Experiment.
5. Conduct the Study Assessment.

Before studying this methodology in detail, the reader less conversant with SLAD terms of art such as "survivability," "lethality," "vulnerability," and "susceptibility" should refer to the appendix. The appendix also discusses some of the subtle distinctions between "SoS," "SoSE," and "SoSA." While our SoSA methodology may be of some interest to those whose primary interest is in SoSE, the principal intended audience for this account of SLAD's SoSA methodology is those who will either conduct SoSA or use SoSA results.

3.1 Phase 1: Define the Problem

SoSA is a contact sport. The problem definition process is a collaborative effort between the analytical team and the study sponsor or customer. As the team progresses through this phase, it must develop a shared understanding of the customer's specific problem. This understanding facilitates decision-making that takes place in subsequent phases regarding resources, analysis strategies, etc. This first phase establishes the foundation upon which the analytical team will build the models, identify modeling gaps, determine resource requirements, analyze the data and frame the results to answer a particular customer's "question". The quotation marks around "question" highlight that an initial customer query may well require sharpening. We employ a three-step approach to arrive at a clearly defined analytical question:

1. Elicit information from the customer to identify and crisply frame the key analysis issues and objectives.
2. Identify the most important issues that must be illuminated for the analysis objectives to be achieved.
3. Develop an experiment directive and obtain customer agreement to document the scope, key objectives, and analysis issues for the study.

3.1.1 Identify the Objective(s)

Objectives should be specific, measurable, achievable, and realistic (*5*).

A *specific* objective is one that is accurate and free from ambiguity. For example, a proposed objective to "determine the impact of radio electronic warfare susceptibilities on a brigade combat team (BCT)" is unacceptably ambiguous. However, the objective "what is the impact of susceptibilities in the Joint Tactical Radio System (JTRS) radio to intelligence warfighting function as it supports a certain specific brigade operation?" is unambiguous and subject to measurement.

A *measurable* objective is one that is supportable with simulation metrics. For the BCT example above, the first proposed objective does not immediately suggest what quantities we should measure, whereas the reformulated example more effectively suggests things to measure. For example, if we adopted the time it took the intelligence officer to relay critical threat information to the battalion commander as an effectiveness measure, then one could count the number of simulated messages that were lost, or measure the simulated time between receipt by the intelligence officer and delivery to the battalion commander.

An *achievable* objective is one that is answerable in the available time. In the example discussed, if results must be delivered in six months, and the current application will only support platoon operations, it is highly unlikely that the analyst will attain the BCT objective, however stated, in the available time because necessary brigade-level models are unlikely to be developed in six months.

A *realistic* objective is one that properly reflects current operational forces, needs, and circumstances. In the BCT example, if either the radio is a poor representation of the JTRS or the model of a brigade combat team is that of a Cold War era force, the analysis obtained will not have the requisite degree of realism.

3.1.2 Identify the Issues

Once we identify the objectives, the next step is to develop specific study issues. To do this, the team frames relevant analytical questions (*5*) to illuminate each objective. This process is not purely deductive; individual analysts may well identify the issues differently. It is to reduce the variance that we employ a multi-disciplinary team. Within the team, a military domain expert will help properly portray the objectives in a tactical domain and to identify the relevant domain concepts that will likely be present in the analysis. The technical domain expert in SLV analysis will contribute expertise that facilitates constructing of issues relevant to a specific use case 1 SLV objective. The researcher will help to formulate the technology trades that are under study for use case 2 projects. The system proponent or evaluator will help formulate the capability package or system issues characteristic of use case 3. We frame all of these specific questions in such a way that we can address them with appropriate measures and metrics.

Credible questions must be the right resolution match to the "functional models" in the current simulation environment[†]. The functional models within a given simulation are primary drivers of the simulation results that will enable us to draw useful analytical conclusions. For example, if our issue concerns the impact of a new class of intrusion detection methods for mobile-ad-hoc-networks, our functional model for communications must be at a level of technical detail where intrusion detection is relevant.

Not every phenomenon modeled will be germane to every SoSA issue and question. These "context-setting models" must be present to provide an appropriate environment for functional models, but their outputs are less critical to the overall analysis scheme. For example, the platform mobility model provides the context for measuring network effects via platform positions, yet its output is not crucial in the analysis.

Finally, there will likely be more than one issue per objective. From the major issues and questions identified there will be several major themes that emerge as the focus for analysis. Whatever the final tally of issues and analysis themes, the final step in identifying the issues is to determine those that *must be addressed* for study success; these issues and the related questions then become the essential elements of analysis (EEA) (*5*).

3.1.3 Experimental Directive

Once the analytical team has identified the objectives, issues, and the EEA, the final element of the problem definition phase is to draft an experimental directive. The role of the directive is threefold:

1. Provide a crisp, clear statement regarding the SoSA goal.
2. Succinctly capture each objective, issue, and EEA.
3. Provide an initial estimate of necessary resources and key study milestones.

The customer approves the directive. We seek and obtain this approval from an organizational level commensurate to the resource commitments required.

[†] We do not intend to suggest that we limit the scope of questions that we can answer to what we have already modeled. Credible questions exist independent of the means to answer them. If there are discrepancies between the resolution required to answer a question, and the resolution of functional models available in the simulation, which implies that either software development to create the functional models in sufficient detail is required or we must modify the question.

3.1.4 An Example Showing Phase 1 in Execution‡

The PM for the XYZ radio asks SLAD for an SLV assessment of its new radio. Initial laboratory analysis reveals that the radio was susceptible to jamming energy when the jamming energy exceeded the signal energy by 15 dB. With the initial laboratory analysis complete, and a set of mitigations proposed, the PM asks SLAD to assess the SoS impact of not applying the mitigations.

To address the PM's question requires a lot of preliminary homework on system specification, scheduling, capability, performance, and planned basis of issue. Suppose the homework reveals that the Army plans to insert the XYZ radio into BCTs as a direct replacement for existing radio systems. Since these radios are in use by all elements of the brigade, it is possible to undertake a SoSA on an important warfighter function where the effects of jamming are readily observable. The fires warfighting function emerged as most critical in discussions with the PM. SLAD defined the SoSA problem as determining the impact of barrage jamming against the fires warfighting function.

Ultimately, this agreement boiled down to the simple experimental directive: "Assess the impact of barrage jamming on the delivery of precision effects by field artillery against a predetermined, moving target array." Furthermore, the PM specifically wished to know the impact that jamming had on various elements of the fires process, and that these elements formed the EEA.

3.2 Phase 2: Develop the Model

In phase 1, we defined the broad elements of a study; these steps included identifying the objectives, developing the issues and the EEA, and creating and approving an experimental directive. In phase 2, we transform these elements into a viable simulation study plan. The study team will summarize the results from this phase via a study plan and a model definition; however, if the study is sufficiently complex, the team may choose to develop separate analysis and data management plans.

3.2.1 The Study Plan

The intent of the study plan (*5–7*) is to identify (1) a detailed mapping of issues to an EEA, (2) the resources required in the study, and (3) a detailed project schedule with significant milestones identified.

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‡ We will use this example to illustrate our methodology as we describe each phase. The example derives from the threat integration work of SLAD's SoSA Integrated Process Team. Because our example focuses on EW, the relevant Integrated Process Team (IPT) members are one of the authors (Smith) as the IPT Chair, Mr. Peter Bothner and Dr. Patrick Honan as EW subject matter experts from SLAD. From New Mexico State University Physical Science Laboratory (NMSU\PSL), Mr. Joel Eichelberger provided communications and software expertise, Mr. Jim Davidson constructed the tactical vignette that we adapted, and Dr. Alex Pogel helped structure and conduct the analysis.

The study plan specifies the relationships between objectives, issues, and the EEA as identified in the experimental directive. A multi-disciplinary analysis team should undertake developing this specification. A military domain analyst will help identify the key military concepts that the SoSA team must understand to illuminate a particular issue, while other technical specialists contribute their understanding of the various underlying technologies and the doctrinal decision processes that the simulated entities employing the technologies will use. Through the process of understanding these cross-domain relationships for the vignette or scenario under consideration, the team gains sufficient understanding to create one or more trial SoS models with which to begin the analysis. By describing tactical missions within one or more warfighting (*8*) functions in a particular mission context we are creating the model SoS that will be the subject of study.

3.2.2 Create a Model

In addition to the study plan, another necessary analytical element is a model SoS. By model SoS, we mean a representation of the SoS in a particular context that reflects valid doctrine, and which is as simple as possible while containing the essential functional and context setting models for the analysis.[§]

For example, suppose a customer needs to understand the changes in effectiveness of a brigade combat team that is equipped with a technology to enhance situational understanding. The intelligence warfighting function is clearly appropriate to consider in the analysis, and an EEA might involve determination of how that technology influences the situational awareness of a platoon within the brigade. We might ask the question: does better or timelier intelligence have an observable effect on the outcome of a simulated combat?

Our model SoS will include at a minimum both Red and Blue forces; these forces will have a command structure, be organized in some mutually supporting manner—for example, see the monograph by Prosser (*10*)—and be equipped with an array of platforms and ancillary equipment. In S4, we use the Vignette Editor Tool (VET) to arrange these forces and equipment into the structure described in our model SoS. We can also use VET to select equipment from the equipment database, place platforms on networks and assign various decision-making processes to platforms and units to create our simulation of a SoS. These decision-making processes determine the specific roles a particular agent representation will play in the simulation, that is, battalion commander, company, commander, platoon leader, scout, etc.

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§ The general issues of complexity and simplicity in models is beyond our scope here. However, the analyst often may be tempted to create an overly complex model for the sake of "domain realism". However, as the quote by Phillip Anderson in his 1977 Nobel Prize winning speech, as cited in the work by Mitchell on page 224 (*9*), indicates a parsimonious model often provides better insight into the questions at hand: "The art of model-building is the exclusion of real but irrelevant parts of the problem, and entails hazards for the builder and the reader. The builder may leave out something genuinely relevant; the reader, armed with too sophisticated an experimental probe or too accurate a computation, may take literally a schematized model whose main aim is to be a demonstration of possibility."

The analytical team's goal in building a model SoS to study is to create a "reasonable" space of tactical and technological possibilities from which will result simulation outcomes to address the issues and EEA. These outcomes are much more complex than identifying whether Blue accomplished its mission ("won") or the simulated force exchange ratio. For the engineering characterization of the equipment to add real value to the intellectual process there are dozens and sometimes hundreds of potentially useful variables tracked throughout the simulation run. In addition to variables that track traditional metrics such as losses, we can also track many unique classes of variables to aid our analyses. For example, we track such time-series measurements as the situational awareness of the commanders in a given experiment. In respect to the decision-making, we analyze the accuracy of the decisions over time using a version of ground truth that is computed (*11*, *12*) via the use of assessor agents. The ability to assess both situational awareness and the accuracy of decisions over time for each element of the simulation is just one example of SLAD's ability to assess the effects CNO and EW have upon the EEA. The art of SoSA is determination of which variables and interactions best illuminate the EEA of interest.

As will be obvious from the previous discussion, developing an appropriate analysis vignette is a complex task unique to each analysis. However, for each analysis we conduct, we will use as one or more vignettes approved by the appropriate U.S. Army Training and Doctrine Command (TRADOC) user.

3.2.3 Develop an Analysis Plan

Another component of the study plan is the analysis plan. It documents the broad analytical themes that the study team will explore during the course of the assessment. The analytical team develops these themes as they work to understand the relationships between the study issues and EEA, and the modeled military missions that will provide the simulation results for assessment.

As the study team relates the issues and EEA to more fundamental simulation outputs, they will generate specific Measures of Merit (*5*) that in turn will be calculated from the metrics generated during the course of a simulation run. In so doing, the team is laying a sufficiently detailed foundation for the resulting assessment so that the study sponsor can ascertain that the analysis can satisfactorily address their issues and needs. A secondary goal in this activity is to ensure that the SoS model and resulting simulation will produce the simulation results of the kind needed to produce the assessment.

The team may choose not to document the plan as a separate deliverable. However, if the analysis is complex, or there are a multiple issues and EEA in the study, it is probably wise to document the analysis plan independent of the study plan. This documentation should serve as part of the basis for the final report.

3.2.4 A Continued Example to Show Phase 2 in Execution

Continuing the example we began in phase 1, the study team turned to Army doctrine and developed a simple model of the fires warfighting function commensurate with the question.

Figure 1 presents this simple model with some of the major coordinating functions that the process must execute in order to conduct a single fire mission.

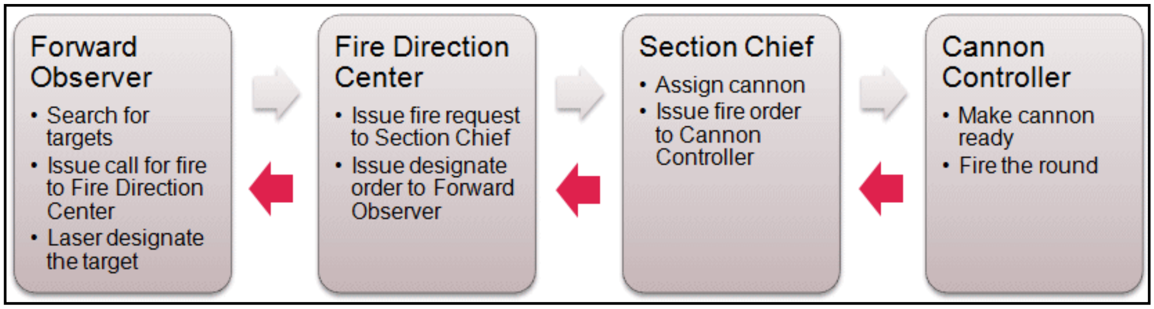


Figure 1. Simplified model of the fires warfighting function depicting significant steps that must occur for the process to complete successfully.

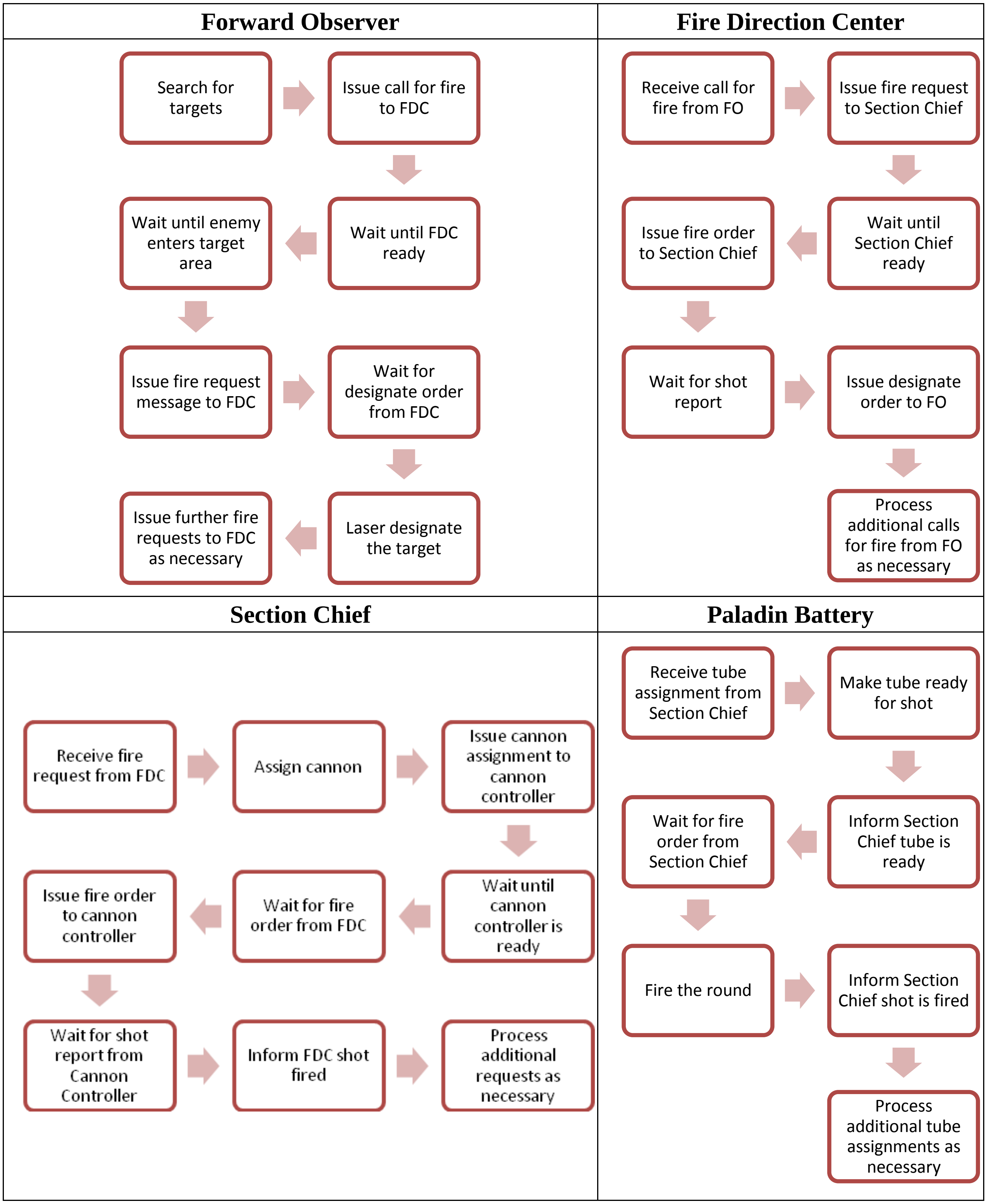
From figure 1, we observe four items that the PM considered EEA, the actions of the forward observer, the fire direction center, the section chief, and the cannon controllers. For *MOP*, the analysis team decided upon measuring both the time to, and the success of, issuing a:

- Call for fire to Fire Direction Center
- Fire request to Section Chief
- Designate order to Forward Observer
- Fire order to Cannon Controller

Each corresponding element of this process must issue their orders successfully for the fires mission given to that warfighting process to achieve its intended effect. Note this intended effect is independent of any particular vignette or mission depiction.

In this case, the fires warfighting function was not yet available in the simulation, so SLAD developed and validated new software for this function, and table 2 represents the key states of this modeled process for each of the four major functional elements.

Table 2. Key software states in a model representation of a fires warfighting function process.



The final element of phase 2 is to define a context within which to gather data to address the question posed, and the essential elements of analysis. Here, we chose a simple vignette. Blue is to identify Red targets moving north and use precision fires to prevent Red from moving a combat effective unit north of Phase Line (PL) Gold (see figure 2). The presence of a combat effective platoon (three or more T-72s with capabilities to fire either their main cannon or Anti-Tank Guided Missiles [ATGMs]) north of PL Gold became the *measure of effectiveness* (*MOE*) for the Blue fires warfighting function. In EW runs, a Red jammer will move along the southern road and jam for a five-minute interval after Blue designates a target.

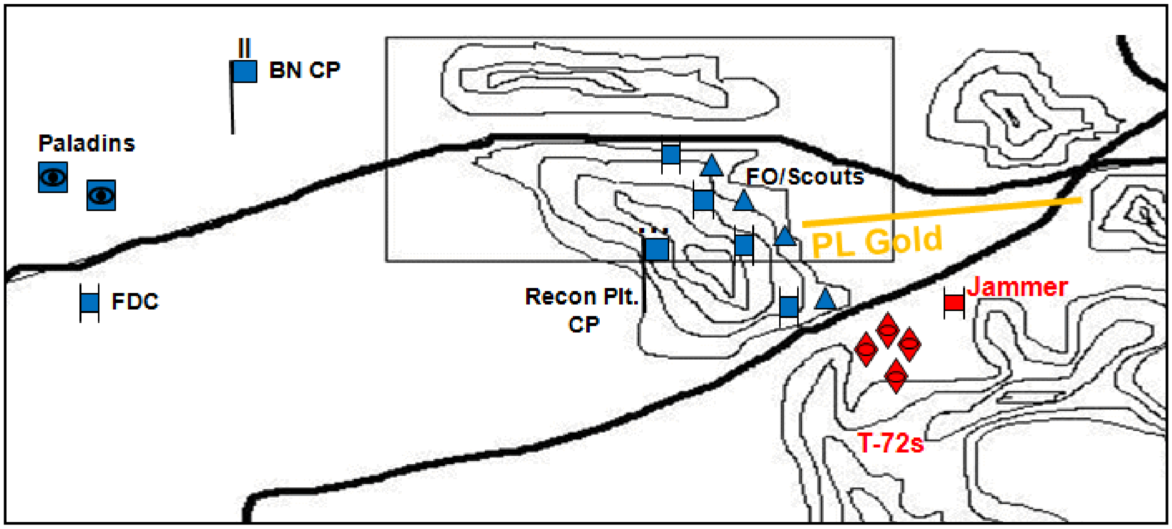


Figure 2. A notional experimental vignette in which a Red tank platoon seeks to move north and impede the transit of Blue forces through the northern mobility corridor.

3.3 Phase 3: Build the Simulation

Through phases 1 and 2 we created a model SoS for our analysis, defined a study framework, and determined the required resources to conduct our study. The next task is to translate the model SoS into a simulation that a computer can execute. The S4 (*3*) environment includes tools designed so that a user can translate a model SoS into simulation code that is machine executable.

From the study directive, the analytical team will create an execution matrix for the simulation experiment. The execution matrix identifies the specific sets of initial conditions that will be run for the study. It is difficult to enumerate a set of initial runs that covers the most promising waterfront without allowing a combinatorial explosion that can prevent the study team from meeting agreed deadlines. The study team should consult with the sponsor to assure that the study will cover the sensitivity analyses of most interest to that party. The team must also draw on its experience with previous studies, and attempt to anticipate which parameters are most apt to drive study results. Specification of the initial matrix is inherently partly judgmental, involving practical tradeoffs as well as intellectual considerations.

For a given simulation experiment, *a priori* prediction of which SoS runs will turn out to be the most interesting or illuminating is notoriously difficult. In many cases, study of the results from the original matrix shows that additional runs should be made for completeness, or to more fully articulate a trend.

3.3.1 A Continued Example to Show Phase 3 in Execution

At this point, all the preparatory work necessary to conduct the experiment is complete. The SoSA team converted the mission context provided in figure 2 to a representation that will execute on a computer. They also instrumented the simulation to audit particular variables relevant to the measures of performance and the MOE that correspond to the EEA. Finally, they established a run matrix that contained both runs with jamming and runs without. They gathered appropriate simulation results and prepared the data for analysis in the next phase.

3.4 Phase 4: Evaluate the Experiment

After the team completes the planned simulation runs, it will have appropriate simulation output to serve as the basis for the analysis. In practice, these files will often be several gigabytes and contain hundreds of metrics, each sampled over thousands of time steps for each Monte Carlo run. The team refines its analysis of the simulated situation in a two-phase process: preliminary data exploration and conclusion formation. We describe the data exploration process here and the conclusion formation process in the next section as Phase 5.

The team usually will go through several steps including:

1. Search for outliers and determine whether they are mistakes or key data points.
2. Familiarize themselves with output trends and anomalies.
3. Categorize the results.
4. Observe and analyze within categories.
5. Identify the emerging trends drawn over all categories.

The team's goal in this phase is to identify the most significant emerging results relative to the study issues and the EEA. Since there is often a time lag between the formation of the study plan and the delivery of simulation output, these preliminary analytical steps allow the team to re-assess—in terms of actual simulation results—where the analysis is going relative to the sponsor's needs.

Familiarization is a time-consuming process: the analysts endeavor to understand the results presented by the simulation. They search for the presence of significant similarities and differences. They will use standard statistical techniques to see what sort of distribution the output metrics exhibit over the run space. They will also determine whether patterns of mission accomplishment (or non-accomplishment) exist. A related aspect of this activity is to identify significant clusters of similar results that seem odd or counterintuitive; these clusters may give us high payoff information that illuminates the various EEA. To assist in this work, team members may use one of the data visualization tools included in the S4 tool set and developed expressly for visualizing quantitative data in the context of a military mission called QuickLook (*13*). QuickLook is software that was inspired by Minard's famous depiction of Napoleons march to Moscow and subsequent return. Tufte (*14*) cites Minard's effort as perhaps the best graphic ever drawn.

When the team is satisfied that they have valid results to analyze, their next step is to identify key characteristics and patterns in the output that will allow them to categorize the runs and results. Good judgment is required here. For example, one characteristic may be that when reaching a key piece of terrain, a unit moves to the left or the right. Either choice may be valid according to doctrine; yet, each choice results in a different pool of data. By placing the simulation output into contextually relevant categories that are also operationally relevant, the multi-disciplinary team guarantees that subsequent analyses rest on a tactically sound footing, grounded in the domain and relevant to the warfighter. This is a more appropriate method for getting to the key information for SLV analysis than statistically slicing and dicing a less differentiated data set.

Within the categorized results, the analysts' task is to discover relationships that may hold value for assessing the mission contributions of the technologies under study. Ultimately, this work establishes the foundation for the phase 5 analysis to follow. Another purpose for the early analysis step is to identify emerging results and present these results to the study sponsor. The goal here is to (1) ascertain the continuing relevance of the study issues, and (2) alert the study sponsor to any particularly significant emerging results.

For example, in an analysis of an active protection system for ground vehicles, the analysis considered three distinct Blue courses of action (COA). Each COA represented a valid doctrinal approach to the same mission. For each COA, the analysis team computed the mean lifetime of the Blue platforms as a MOE. They were statistically different when they were rank-ordered by the MOE. However, when the team included explicit focus on vehicles equipped with the active protection system in the analysis, they discovered that runs with the platforms so-equipped yielded results in the upper quartile of mean lifetime. This result held independently of COA. Thus, what initially appeared to be statistically disparate pools of simulation outputs yielded a conclusion that was more general than the disparate pools would have suggested. This observation is relevant to the PM developing or considering active protection technology in that it suggests a wider applicability for their product.

The analysis team cannot apply an algorithm as it mines simulation results. Ultimately, the goal of this phase is to identify the most interesting, important, or surprising relationships in the results, and to determine the significance of metrics that are appropriate to these regimes. The process results in a tentative set of analysis conclusions grounded in military mission accomplishment.

3.4.1 A Continued Example to Show Phase 4 in Execution

Recall the plight of our Paladin battery. During preliminary analysis, the team plotted the number of shots taken by the Paladin batterys against the Red force moving north. When the analysts considered this metric in the presence or absence of jamming, it appeared that jamming did have a significant effect on the fires warfighting function process. Figure 3 presents this preliminary analysis. Faced with the data in figure 3, the analysts asked the further question: what part of the process does jamming impact? A fuller answer to this question would emerge in phase 5, but the initial operational explanation is that there were far fewer Blue indirect fire shots in the jamming runs, as compared with the runs without jamming.

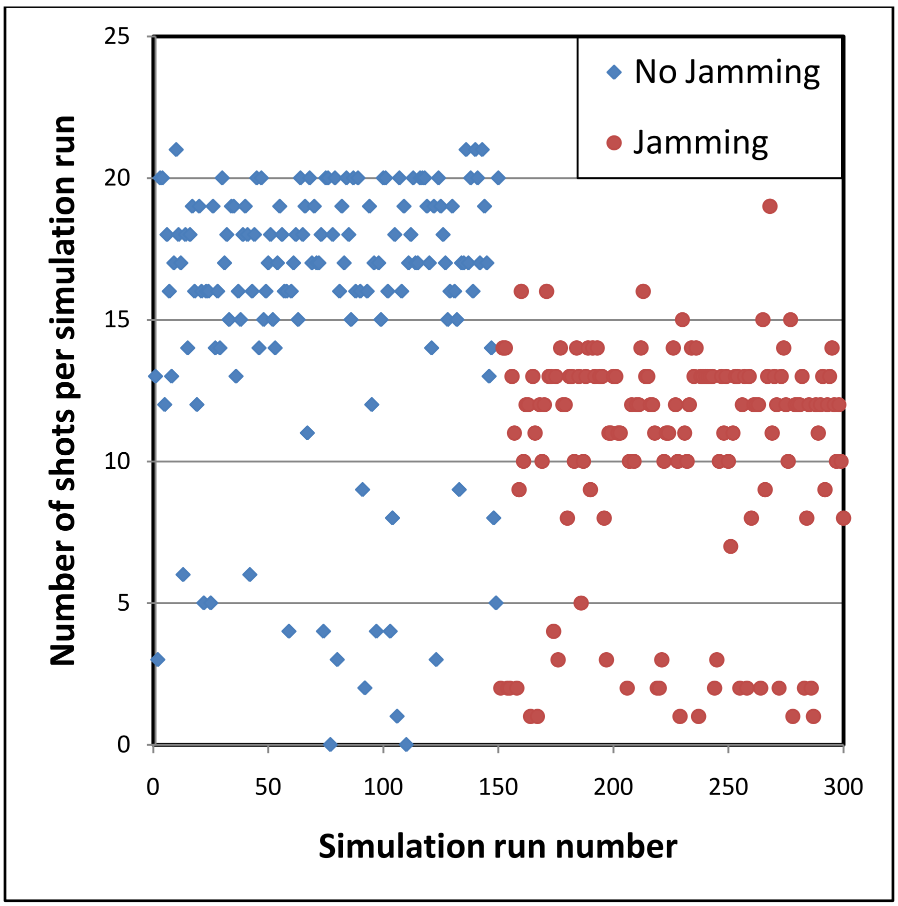


Figure 3. A representative preliminary data analysis step. Each mark on the graph represents a count of shots taken by the Paladin battery in the given simulation run. The horizontal axis is the simulation run number. Simulation run numbers at or below 150 are "no jamming" runs, while run numbers above 150 are "jamming" runs.

3.5 Phase 5: Conduct the Study Assessment

In this final phase, we describe specific conclusions and perhaps recommendations that relate to the EEA developed in phase 2. Recommendations might be for substantial actions or decisions by the study sponsor or they might identify matters requiring further study. At this point in the assessment process, the analysis team will have developed considerable insight into the simulation output and will have drawn tentative conclusions. The team may have presented these insights and tentative conclusions to the study sponsor, and made subsequent revisions or responded to further requests. What remains is for the team to state and carefully vet their conclusions in the context of the study goals and the EEA, and form them into a coherent presentation.

The use case 1 problem of conducting SLV assessments in a SoS context means identifying the impact on mission success caused by individual item-level susceptibilities. One can think of the analysis as aggregating many observations as the modeled leaders direct various threats against specific susceptibilities. Each run of our simulation model may result in tens or hundreds of these attempts, generated from a broad distribution of initial conditions. The analytical team must seek to identify trends and anomalies that arise from many runs of a complex simulated scenario.[**] Some anomalies may result from coding or input errors; others may be essentially illuminating for the questions under study.

In practice, the analytical team will condition their approach on both the type of use case and the specific issues and the EEA for the study. It is likely that individual SoSA analysts will approach a given problem differently. It is here that the strength of a multi-disciplinary team comes in to play; the give and take of team dynamics often reveals insights and conclusions that are substantially different and deeper than individual analysts would have been able to reach on their own. This process helps drive the analysis to well-founded conclusions that are rooted in the military domain, relevant to the warfighter, and grounded on solid engineering data.

[**] One such tool that facilitates this process by allowing the data to drive the formation of concepts, and exploration of the space of concepts, is called Formal Concepts Analysis (FCA) (*15*). It is beyond the scope of this report to discuss FCA except to say that it is a concept formation and exploration method that identifies co-occurrences of sets of attributes of individual observations, called intents, and sets of individual observations, called extents. The computation of these concepts through intent-extent pairs has a well-developed mathematical foundation (mathematical lattice theory [*16*]), and this decomposition of the notion of concept is based upon centuries of philosophical developments (*17*) and established in the international standard ISO 704. The use of FCA, as it applies to SoSA and S4, centers around two software packages. One package is called Seqer (*18*), a tool that allows an analyst to observe and graphically explore assertions based on intent-extent pairs formed over the space of simulation data, and RAGE (*19*), a tool that allows an analyst to form assertions based on intent-extent pairs formed over the space of simulation data. Seqer provides a complex, but convenient way to visualize the simulation output data in a manner that allows an analyst to discover relationships that may otherwise hide in a mass of numerical simulation data. As discussed in phase 4, the analyst may make observations within specific categories of simulation data. The analyst expectation is that these observations may hold over many such categories; however, the observations may hold with varying strengths. These initial observations become the intent, and the extent is the hypothesis the analysts wishes to test. In this case, RAGE allows the analyst to draw these conclusions from the data along with confidence intervals, odds ratios, and other similar statistical measures.

The final report will identify the issues, present the essential elements of analysis, describe the study framework, and characterize the SoS model or models employed. It will also include the conclusions reached and the specific model outputs that support them. Finally, the team should archive the simulation, including inputs and outputs.

3.5.1 A Continued Example to Show the Completion of an Analysis Cycle in Phase 5

To identify elements of the fires process degraded by jamming, the analysts identified corresponding landmark states in the software model for the fires warfighting function that corresponded to the EEA. Then they measured the time to complete the function through that landmark state. Figure 4 summarizes this data. From the data, the analysts concluded that the jammer was sufficiently effective to deny completion of the fires process. The most significant finding was the inability of forward observers to fulfill their functions. Based on this analysis, the results reported to the PM for the XYZ radio suggested development of a mitigation strategy to remediate the effects of barrage jamming, and that at the completion of that mitigation, to re-assess the radio for other issues.

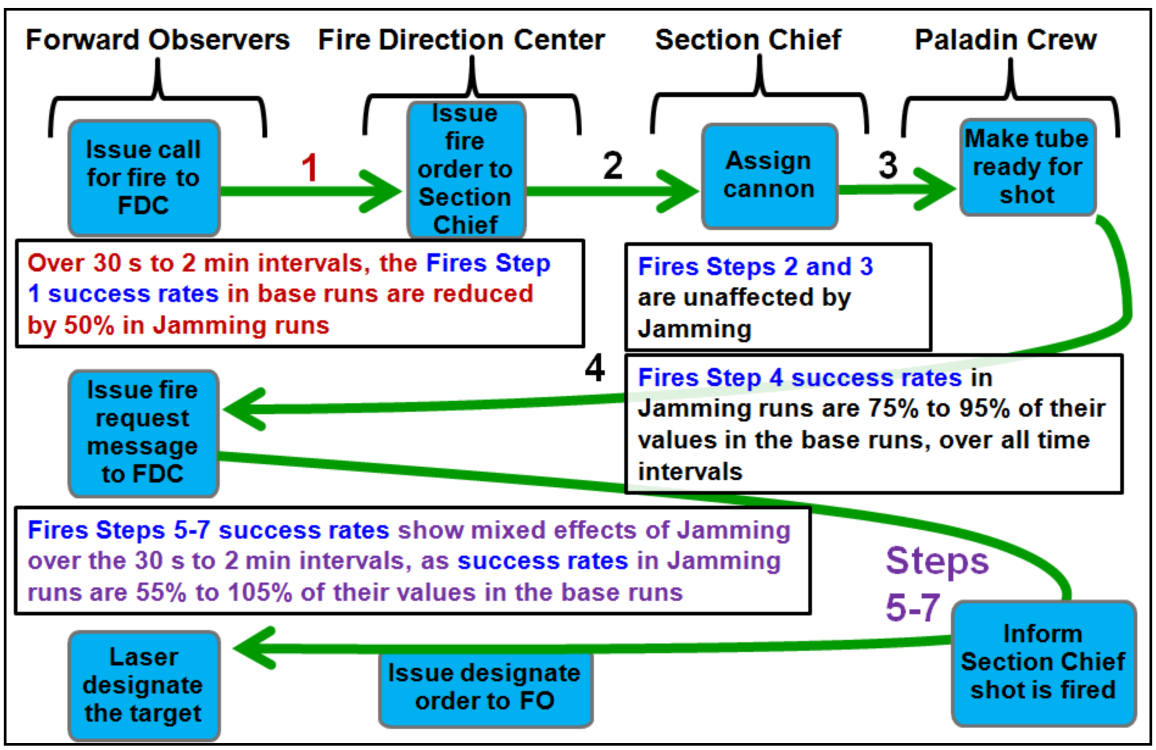


Figure 4. Engineering analysis of the fires warfighting function in the presence of jamming. Note that the states identified here are landmark states. Each is one measurable state represented in the software model representation of our fires warfighting function representation (see table 2).

4. Summary

This report provided a "how to" overview of the methodology employed by teams of analysts conducting SoSA. We characterized and discussed the methodology, consisting of five distinct phases, and informed by the Military Operational Research Society (MORS) Lexicon (*5*), by using the metaphor of a pentagon, as shown in figure 5. Each phase of the methodology described in the previous section corresponds to a roman numeral in figure 5; the faces of the pentagon linking each major phase represent the actions undertaken by the analysis team to complete each phase.

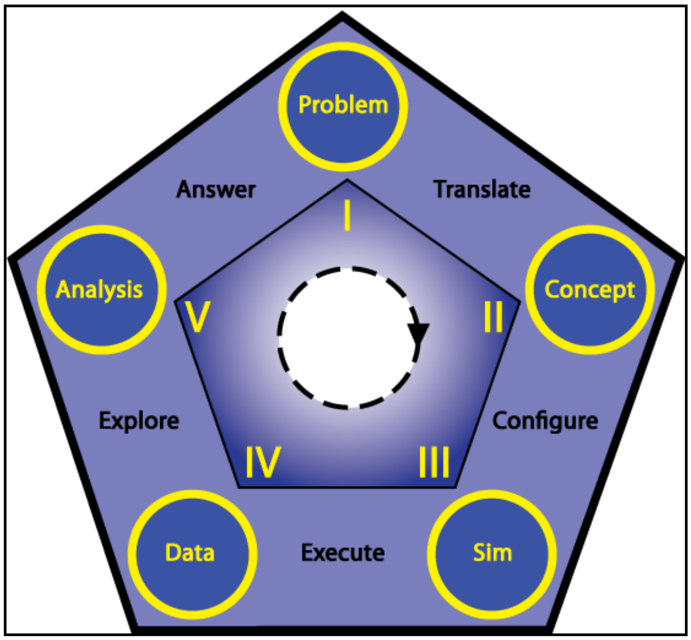


Figure 5. The SoSA pentagon, a graphical depiction of a developing methodology.

This methodology consists of five distinct phases:

1. Define the Problem.
2. Develop the Model.
3. Build the Simulation.
4. Evaluate the Experiment.
5. Conduct the Study Assessment.

SLAD's methodology is still under development. However, in numerous applications to focused problems the methodology has provided SLAD analysts the ability to conduct credible SoSA for small forces (battalion or less) in an operationally representative environment. Applications of this methodology to problems of ballistics analysis in a SoS context were presented to the National Defense Industry Association and the Live, Virtual and Constructive Simulation conferences (*20*, *21*). We also gave a more general overview to the Army Operations Research community (*22*) and to the National Defense Industry Association conference (*23*).

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Appendix. Definitions and SoS, SoSE, and SoSA Discussion

A-1. Definitions

The term *system of systems* (*SoS*) is the subject of much recent discussion; see for example chapter one of works by Jamshidi (*24*, *25*) and an ARL workshop in 2009 (*26*). While a consensus meaning has not yet evolved, in this paper we will use the definition for SoS developed within SLAD as part of a broader ARL effort:

> A SoS "is a collection of interlinked and mutually dependent systems that has properties and capabilities well beyond the simple union of the independent attributes of its constituent systems."

This paper frequently uses the words *survivability, vulnerability, lethality, and susceptibility* (*SLV*) and their cognates. We follow the definitions provided by the work of Deitz et al. (*27*):

> Survivability: The total capability of a system (resulting from the synergism among personnel, materiel, design, tactics, and doctrine) to avoid, withstand, or recover from damage to a system or crew in hostile (man-made or natural) environments without suffering an abortive impairment of its ability to accomplish its designated mission.
>
> Vulnerability: The characteristics of a system that cause it to suffer degradation (loss or reduction of capability to perform the designated mission) as a result of having been subjected to a hostile environment on the battlefield.
>
> Lethality: The ability of a weapon system to cause the loss of, or degradation in, the ability of a target system to complete its designated mission.
>
> Susceptibilities: The characteristics of a system that make it unable to avoid being engaged by threats on the battlefield.

The phrase *system of systems* is contained in some related phrases such as *system of systems engineering* and *system of systems analysis*

A-2. SoS Engineering and SoS Analysis

SoS engineering (SoSE) (*24*, *25*) typically focuses on the process of engineering development for both constituent technologies and their connections within the SoS. For example, engineers are currently designing the next generation automated traffic systems (*28*). The designers of such systems typically abstract the human part of the SoS via simple rules that are valid over a wide range of likely situations. A very similar process occurs in the engineering of many military SoS (*26*, *29*). For these systems, the emphasis remains largely on "packages" of constituent technologies, with human factors aspects captured in a few standardized scenarios. The material developers define (or receive) requirements for the constituent technologies over a range of military domain contexts. They recognize that in actual military operations the soldiers that employ a SoS may well face scenarios that vary considerably from the standard scenarios used in design, and that in the novel scenarios there may be less than optimal performance.

For military SoS analysis (SoSA), the adaptation of using Soldiers in their doctrinal roles within a specific scenario as they employ the SoS technology is of essential interest (*2*). Not only can alternative arrangements of the constituent technologies yield different analytical results, different simulated adaptations can too. Therefore, a credible analysis must consider the technology, the requisite mechanisms for human adaptation to both the technology and the local circumstances, and the scenario itself as key elements of the analysis. Consequently there is a more inclusive focus here than in system engineering.

Figure A-1 metaphorically captures the notions embodied above. The three faces of the cube represent the technologies, the doctrinal and domain knowledge modeled for the human agents, and the mission environment in which the Soldiers will employ the SoS. In SoS engineering, the emphasis is principally on the technology face. The other two faces are considered principally in the development of robust requirements. In SoS analysis, we represent each face in the simulation with enough detail to insure that all three domains can be influential in the analysis.

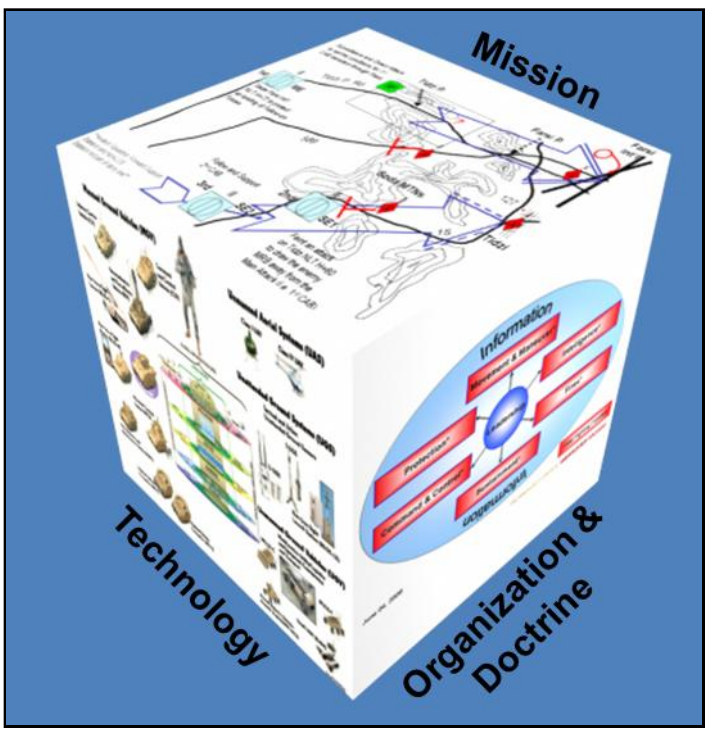

Figure A-1. The inter-relationship of technology, organization, and doctrine forms a military SoS, and the expression of that SoS in a mission context is required for SLV analysis.

List of Symbols, Abbreviations, and Acronyms

ARFORGEN	Army Force Generation
ARL	U.S. Army Research Laboratory
ATEC	Army Test and Evaluation Command
ATGM	Anti-Tank Guided Missiles
BCT	brigade combat team
CNO	computer network operations
COA	course(s) of action
EEA	essential elements of analysis
EW	electronic warfare
FCA	Formal Concepts Analysis
IPT	Integrated Process Team
JTRS	Joint Tactical Radio System
MOE	measure(s) of effectiveness
MOP	measure(s) of performance
MORS	Military Operational Research Society
NMSU/PSL	New Mexico State University Physical Science Laboratory
PEO	Program Executive Office
PL	Phase Line
PM	program manager
S4	System of Systems Survivability Simulation
SLAD	Survivability/Lethality and Analysis Directorate
SLV	survivability, lethality, and vulnerability
SLVA	survivability, lethality, and vulnerability analyses
SoS	system of systems

SoSA	system of systems analysis
SoSE	system of systems engineering
SUT	system under test
TRADOC	U.S. Army Training and Doctrine Command
VET	Vignette Editor Tool

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